BOTULINUM NEUROTOXIN B RECEPTORS AND USE THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional application 60/422,951, filed on October 31, 2002, and U.S. provisional application 60/498,128, filed on August 27, 2003, both of which are herein incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with United States government support awarded by the following agencies: NIH MH61876 and GM56827. The United States government has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0003] Clostridial neurotoxins (CNT) are the most toxic substances known. There are eight related toxins - seven botulinum neurotoxins (BoNT/A-G) and tetanus neurotoxin (TeNT) (Schiavo et al., 2000; Simpson, 1981). BoNTs can cause botulism disease and are potential biological weapons (Arnon et al., 2001; Mahant et al., 2000). Each of the BoNT and TeNT is composed of a heavy and light chain; the heavy chain mediates binding to the surface of specific nerve terminals. Once internalized via endocytosis, the light chain is translocated from the lumen of the vesicle into the cytoplasm where it functions as a zinc-dependent protease (Schiavo et al., 2000). The light chain cleaves one or more components of a conserved membrane fusion complex composed of syntaxin, SNAP-25 and synaptobrevin (syb), thereby blocking exocytosis (Blasi et al., 1993a; Blasi et al., 1993b; Schiavo et al., 1992; Schiavo et al., 1993). Because of their ability to selectively disrupt Ca^{2+}-triggered exocytosis, the CNTs have emerged as important tools for the study of membrane fusion and synaptic transmission (Jahn and Niemann, 1994).

[0004] The first step in the action of CNTs involves binding to receptors on the surface of neurons. Current evidence suggests that the receptors are composed of gangliosides and proteins that cooperate to form high affinity toxin binding sites. Alternatively, gangliosides may constitute relatively low-affinity toxin binding sites that serve to capture CNTs to facilitate interactions with cell surface receptor proteins (Montecucco, 1986; Nishiki et al., 1996a). Gangliosides are ubiquitous glycosphingolipids in the outer leaflet of plasma membranes. They are classified according to the number and

position of sialic acids present in their head groups. Polysialiogangliosides, which are present almost exclusively in neurons and neuroendrocrine cells, bind to CNTs with the greatest avidity (Halpern and Neale, 1995). While a protein component is also clearly involved in toxin-cell recognition, at present, a protein that mediates toxin entry has not been identified (Schiavo et al., 2000).

[0005] Biochemical studies have led to the identification of a handful of CNT binding proteins. In most case, these binding proteins do not appear to function as receptors that mediate entry of the toxins. For example, BoNT/A,B,E and TeNT were reported to bind synapsin I and adducin, respectively (Schengrund et al., 1996; Schengrund et al., 1993; Schengrund et al., 1992). Since neither of these proteins are exposed to the outside surface of cells, they are unlikely to function as cell surface receptors. TeNT was reported to bind Thy-1, a GPI-anchored plasma membrane protein. However, neurons from mice lacking Thy-1 are still sensitive to TeNT, suggesting that Thy-1 is not essential for TeNT entry into cells (Herreros et al., 2001).

[0006] Synaptotagmins (syt) I and II (Nishiki et al., 1994) are homologous synaptic vesicle membrane proteins thought to function as Ca^{2+}-sensors for exocytosis (Chapman, 2002; Schiavo et al., 1998). Syt I and II were reported to bind BoNT/B in the presence of gangliosides; the dissociation constant for the syt I•BoNT/B complex was 2.3 nM and the dissociation constant for syt II•BoNT/B was 0.23 nM (Nishiki et al., 1996a). High affinity binding of BoNT/B to fibroblasts was reconstituted by expression of syt II and incorporation of exogenous gangliosides into surface membranes. However, binding did not result in the cleavage of the BoNT/B target protein, syb II, that had been co-expressed with syt II, indicating that the toxin was not internalized (Nishiki et al., 1996b). Although biochemical studies clearly established that syt binds to BoNT/B, evidence that binding mediates entry into cells is lacking. Thus, whether this interaction has any functional role remains unknown. More recently, BoNT/A and E have also been reported to bind syt I, albeit in a ganglioside independent manner (Li and Singh, 1998).

[0007] Syt II is a 422-amino acid protein that contains a luminal domain (a.a. 1-60), a transmembrane domain (a.a. 61-87) and a cytoplamic domain (a.a. 88-422). The cytoplasmic domain contains two C2 domains: C2A (a.a. 88-267) and C2B (a.a. 275-422) linked by a linker region (a.a. 268-274).

[0008] Determining whether any of the above proteins, or perhaps other proteins, serve as the BoNT receptor will be extremely useful for designing molecules that can reduce or completely inhibit BoNT toxicity. For the same reason, once a receptor is identified, it is

important to map the BoNT binding domain because polypeptides containing the domain and peptidomimics thereof can be used to compete with the receptor for BoNT binding, thereby reducing or completely inhibiting BoNT toxicity.

BRIEF SUMMARY OF THE INVENTION

[0009] The present invention is based on the identification of syt I and II as BoNT/B receptors as well as the identification of the BoNT/B binding domains on syt I and II.

[00010] In one aspect, the present invention relates to an isolated nucleic acid that contains a coding sequence either for the BoNT/B binding domain of syt I or II of the rat, mouse or human species or for an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the foregoing BoNT/B binding domain. An isolated nucleic acid having a nucleotide sequence that is at least 80% identical to the coding sequence of the BoNT/B binding domain of syt I or II of the rat, mouse or human species or hybridizes to the coding sequence under stringent or moderately stringent hybridization conditions is also within the scope of the invention. The nucleic acid of the present invention can be provided in a vector or host cell and operably linked to a non-native expression control sequence. For human syt I and II, the BoNT/B binding domains are amino acids 33-53 and 37-57, respectively. For rat or mouse syt I and II, the BoNT/B binding domains are amino acids 32-52 and 40-60, respectively.

[00011] In another aspect, the present invention relates to an isolated polypeptide that contains either the BoNT/B binding domain of syt I or II of the rat, mouse or human species or an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the foregoing domain. An antibody specific either to the BoNT/B binding domain of syt I or II of the rat, mouse or human species or to an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the foregoing domain is also within the scope of the present invention.

[00012] Other aspects of the invention relate to methods of reducing BoNT/B toxicity, methods of identifying agents that can block the binding between BoNT/B and syt I or II, methods of identifying agents that can bind to the BoNT/B binding domain of syt I or II, and methods of detecting BoNT/B or *Clostridium botulinum*.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[00013] Fig. 1 shows interactions between syt isoforms and BoNT/A, B and E. A) Upper panel, schematic diagram of the syt constructs used in the GST-pull down

experiments. To facilitate purification, all syt constructs lacked a C2B domain; the arrow indicates the C-terminus of the truncated syts. The transmembrane domain (TMD) is indicated by a black rectangle. Middle panel, GST or the indicated GST-fusion proteins were incubated with 30 nM BoNT/B, A and E, either with (+; 25 μg/ml) or without (-) gangliosides in 100 μl of TBS. Seventeen percent of the bound materials were analyzed by SDS-PAGE and immunoblotting using anti-CNT polyclonal antibodies. "Total" corresponds to 80 ng of toxin. In the lower panel, the amount of fusion protein was varied as indicated. B) Binding assays were carried out as in (A). N-terminal fragments of syt II and IX served as positive and negative controls, respectively, and two chimeric constructs, in which the luminal domains of syt II and IX were swapped, were tested for toxin binding activity. C) Binding assays were carried out as in (A) using immobilized syt II 1-87 and the indicated concentrations of BoNT/B. Bound toxin was visualized by staining with Coomassie blue; binding was stoichiometric at saturation. The heavy chain (H) of BoNT/B runs at 100 kDa, the light chain (L) runs at 50 kDa. The asterisk denotes a proteolytic fragment of GST-syt II 1-87.

[00014] Fig. 2 shows mapping of the BoNT/B binding site within the luminal domain of syt II. A) Binding assays were carried out as in Fig. 1A, using the indicated syt II truncation mutants. The upper panel shows a schematic of the truncation mutants where (+) denotes binding and (-) denotes lack of binding. B) Sequence of the amino terminus of syt I and II. The underlined region (residues 40-60 in syt II; residues 32-52 in syt I) is critical for binding BoNT/B; the asterisks indicate sequence differences. The TMD is boxed. C) Upper panel - A peptide, P21, corresponding to residues 40-60 of syt II plus a C-terminal cys residue was conjugated to agarose beads and used to pull-down toxin as described in (A); a scrambled peptide, P21S (IKMNDAEFFGKSNFQEKLEKEC, SEQ ID NO:5), served as a negative control. Lower panel - P21, but not P21S, blocked the interaction between BoNT/B and the 1-87 fragment of syt II. Binding assays were carried out as in (A), but as a function of the indicated P21 or P21S concentration.

[00015] Fig. 3 shows that entry of BoNT/B into PC12 cells is dependent on syt I expression and pre-loading of cells with gangliosides. A) PC12 cells were either untreated or pre-loaded with gangliosides. Cells were then incubated with 50 nM BoNT/B for 48 hr, fixed with 4% paraformaldehyde, permeabilized with 0.1% Triton X-100, and stained using a rabbit anti-BoNT/B antibody; the secondary antibody was goat anti-rabbit-FITC. Pre-loading cells with gangliosides resulted in toxin binding activity. B) PC12 cells either were (+) or were not (-) preloaded with gangliosides; cells were then incubated with (+) or without (-) 50

nM BoNT/B for 48 hr and harvested. Twenty μg of each sample was subjected to SDS-PAGE and immunoblot analysis using anti-syb II (Cl 69.1) or anti-syt I (Cl 41.1) antibodies. Pre-loading cells with gangliosides mediated entry of toxin, as evidenced by cleavage of syb II. Syt I was probed to ensure equal loading on the gels. C) Experiments were carried out as in (B) above, except that wild type PC12 cells were compared to the syt I^- cells (Shoji-Kasai et al., 1992). α/β-SNAP was probed to ensure equal loading. In the absence of syt I, BoNT/B cannot enter PC12 cells to cleave syb II, even when cells have been pre-loaded with gangliosides. D) Entry of BoNT/A and E into Syt I^- PC12 cells. Syt I^- PC12 cells were incubated with 30 nM BoNT/A or 50 nM BoNT/E for 48 hrs; entry was monitored by assaying for cleavage of SNAP-25. Asterisks denote SNAP-25 cleavage products.

[00016] Fig. 4 shows that Syt II mediates entry of BoNT/B into PC12 cells. A) Full length mouse syt II was subcloned into pCDNA3.1(-) and used to transfect PC12 cells. Cells were selected with G418 and several independent monoclonal lines were established and screened for syt II expression by immunoblot analysis using a rabbit anti-syt II antibody; 30 μg of protein from the syt II^+ clones and 100 μg from the syt II^- clones were loaded onto the gels. Clone No. 1, 5 and 10 expressed syt II (syt II^+), clone No. 8, 9 and 13 lacked syt II (syt II^-). Since clone No. 5 expressed low levels of syt II (left panel), a 100 μg sample from this clone was also included in the blots of the syt II^- clones to confirm that this clone expresses syt II. B) Wt or syt II^+ (clone No. 1) PC12 cells were decorated with 30 nM BoNT/B as described in Fig. 3A. C) Entry of BoNT/B (15 nM) into PC12 cells was assayed as described in Fig. 3B. Entry of the toxin was observed in all syt II^+ clones, and was not observed in any of the syt II^- clones. As a control, a parental PC12 cell line was analyzed in parallel.

[00017] Fig. 5 shows that syt II fragments that contain the BoNT/B binding site block binding and entry of the toxin into syt II^+ cells. A) Cells were decorated with BoNT/B as in Fig. 3A in the absence or presence of the indicated syt II fragments. Syt II 1-267 and 61-267 were purified using a his6-tag at the amino terminus and syt II 1-87 was purified as a GST-fusion protein and eluted from beads using glutathione. Syt fragments 1-267 and 1-87, as well as the P21 peptide (residues 40-60), blocked binding; 61-267 and P21S had no effect. The syt II 1-267 and 61-267 fragments form aggregates bound to cell membranes (Bai et al., 2000) as visualized with an anti-his6 antibody in the bottom panel; for syt II 1-267, these aggregates also contained BoNT/B. The final concentrations of recombinant protein and peptides in the media were 960 nM and 10 μM, respectively; the final concentration of BoNT/B was 30 nM. B) Syt II^+ PC12 cells (clone No. 1) were treated with 30 nM BoNT/B that was premixed with the indicated concentration of the syt II 1-267 fragment in the

absence (upper panel) or presence of gangliosides (25 μg/ml; lower panel) for 48 hrs. Samples were analyzed by immunoblotting as described in Fig. 3B. Cleavage of syb II was inhibited by the 1-267 fragment of syt II; inclusion of gangliosides increased the ability of the syt fragment to block cleavage of syb II. Fragment 61-267 had no effect. C) Experiments were carried out as in (A), but using the P21 or P21S peptides.

[00018] Fig. 6 shows activity dependent uptake of BoNT/B, followed by cleavage of syb II in rat diaphragm motor nerve terminals. Rat diaphragm preparations were incubated with BoNT/B (5 nM) in mammalian ringer. They were either unstimulated (control), stimulated with high potassium (stimulated), or stimulated in the presence of a mixture of BoNT/B and the protein fragment syt II 1-267 or 61-267 (1 μM) plus gangliosides (25 μg/ml). They were then fixed, permeabilized and blocked. Control (unstimulated) nerve terminals show bright immunofluorescence for syb II, and very dim labeling of BoNT/B. Stimulation during incubation with BoNT/B resulted in greatly reduced syb II immunofluorescence, while BoNT/B levels are markedly enhanced. Stimulation in the presence of both BoNT/B and syt II 1-267/gangliosides resulted in protection of nerve terminals, seen as both preservation of syb II staining, and greatly reduced levels of BoNT/B binding. A) Quantification of BoNT/B levels under different conditions. Stimulation greatly enhances BoNT/B binding, and this can be blocked by co-incubation with syt II 1-267/gangliosides. Syt fragment 61-267 plus gangliosides failed to block binding of BoNT/B. B) Quantification of syb II levels. Syb II levels show a complementary pattern to those seen with BoNT/B. Levels of immunofluorescence are high in unstimulated tissue, but drop after stimulation. Inclusion of syt II 1-267/gangliosides but not 61-267/gangliosides with BoNT/B protects syb II from cleavage. In panels (A) and (B), error bars represent the standard error of the mean (N = 15-22).

[00019] Fig. 7 shows protection of mice from BoNT/B toxicity using fragments of syt II. A) Specific toxicity of BoNT/B in female mice was determined by an intravenous time-to-death assay (Boroff and Fleck, 1966). The standard curve was used to convert time-to-death (min) to LD_{50}/ml. The resultant LD_{50}/ml values were used to calculate % neutralization of toxicity using the expression: 1- [LD_{50}/ml(+ syt II fragment)/ LD_{50}/ml (- syt II fragment)] x 100, where (+ syt II fragment) refers to samples that contain toxin, gangliosides and recombinant proteins and (-syt II fragment) samples were composed of toxin and gangliosides only. B) The indicated syt fragments (5 μM) were pre-mixed with gangliosides (250 μg/ml) and BoNT/B concentrations that lie in the linear range of the standard curve in panel A (i.e. 10^5-10^6 LD_{50}/ml) for 10 min at room temperature, and injected intravenously

(100 μl) into mice. Percent neutralization was determined as described in panel A. In all the *in vivo* experiments, the indicated concentrations correspond to the initial concentration prior to i.v. injection; the dilution factor in the circulatory system is about 1:10. C) Experiments were carried out as described in panel B, but as a function of the syt II 1-267 or 1-87 concentration. D) Pre-injection of gangliosides (250 μg/ml) plus syt II 1-267 (17 μM) or 1-87 (20 μM) mixtures protects mice from subsequent exposure to BoNT/B. Experiments were carried out as in (B), except that toxin was injected 1 min after injection of the receptor complex. Note: in panels (B-D), each data point represents the average of at least triplicate determinations; error was within +/-10%.

[00020] Fig. 8 shows the mapping the BoNT/B binding site within the luminal domain of syt I. Binding assays were carried out as described in Fig. 2A, using the indicated syt I truncation mutants. The upper panel shows a schematic of the truncation mutants where (+) denotes binding and (-) denotes lack of binding.

[00021] Fig. 9 demonstrates the simultaneous and specific internalization of syt I luminal domain antibodies and BoNT/B into PC12 cells. A) BoNT/B and α-syt I_N antibodies simultaneously bind to syt I. Co-immunoprecipitation of the syt I 1-265 fragment (1.5 μM) with BoNT/B (300 nM) was carried out as described in Methods. Immunoprecipitated toxin and syt I 1-265 were detected on western blots using ECL. B) PC12 cells were pre-loaded with gangliosides and incubated with BoNT/B (50 nM) plus α-syt I_N (10 μl/ml) antibodies for 10 min at 37°C in high [K^+] buffers. Cells were then washed, fixed and permeabilized as described in Methods section of the Example below. Top panel: PC12 cells were able to take up α-syt I_N antibodies and BoNT/B after depolarization. Middle panel: Experiments were carried out as above, except the α-syt I_C antibodies were used - this antibody was not taken up following depolarization, and thus serves as a negative control. Bottom panel: Experiments were carried out as described in panel (A) above, except that syt I^- cells were used. Syt I^- cells were unable to take up either the α-syt I_N antibody or BoNT/B.

DETAILED DESCRIPTION OF THE INVENTION

[00022] It is disclosed here that among many proteins that can bind BoNT/B, syt I and II are the BoNT/B receptors that mediate the toxin's cellular entry and neuro-toxicity. The BoNT/B binding domain and the ganglioside binding domain of syt I and II are also disclosed. While syt I needs both the BoNT/B and ganglioside binding domains as well as gangliosides for BoNT/B binding, syt II only needs its BoNT/B binding domain to bind

BoNT/B. The ganglioside binding domain along with gangliosides can enhance the binding between BoNT/B and syt II. The disclosure here provides new prevention and treatment strategies for BoNT/B toxicity and botulism disease. The disclosure here also provides new tools for identifying agents that can be used to reduce binding between BoNT/B and syt I or II and hence BoNT/B cellular entry and toxicity.

[00023] It is known in the art that the function and amino acid sequences of syt I and II are conserved across animal species. Although the disclosure here is based on the findings with rat syt I and mouse syt II, the findings apply to all animal species that have conserved syt I or II BoNT/B or ganglioside binding domains with regard to the corresponding domains of rat syt I and mouse syt II. For example, for the syt I and II BoNT/B binding domains and their ganglioside binding domains, the human, rat and mouse amino acid sequences are at least 94% identical. As additional examples, the syt I BoNT/B binding domains of chicken (GenBank Accession No. P47191) and *Discopyge ommata* (GenBank Accession No. P24506 and P24505) are 80% and 78% identical to the rat BoNT/B binding domain, respectively, and the syt I ganglioside binding domain of *Discopyge ommata* is about 80% identical to that of rat syt I. It is expected that for a BoNT/B binding domain or a ganglioside binding domain of either syt I or syt II of the human, rat and mouse species, any polypeptide that is at least 70% identical to one of these domains over the entire length of the domains will retain their functions in BoNT/B and gangliosides binding.

[00024] The mouse and rat syt I nucleotide sequences are provided as SEQ ID NO:1 and 3 (GenBank Accession No. D37792 and X52772), respectively, and the corresponding amino acid sequences are provided as SEQ ID NO:2 and 4. The mouse and rat syt II nucleotide sequences are provided as SEQ ID NO:6 and 8 (GenBank Accession No. D37793 and M64488), respectively, and the corresponding amino acid sequences are provided as SEQ ID NO:7 and 9. The human syt I and syt II amino acid sequences are provided as SEQ ID NO:5 and 10 (GenBank Accession No. NP_005630 and Q8N9I0), respectively. For murine (rat or mouse) syt I and II, the BoNT/B binding domains are amino acids 32-52 and 40-60, respectively, and the ganglioside binding domains are amino acids 53-79 and 61-87, respectively. For human syt I and II, the BoNT/B binding domains are amino acids 33-53 and 37-57, respectively, and the ganglioside binding domains are amino acids 54-80 and 58-84, respectively. The amino acid sequences of syt I and II of some other animal species are available in the art and a skilled artisan can readily determine the BoNT/B and ganglioside binding domains thereof using any alignment program or other methods based on the disclosure here.

Polypeptides, nucleic acids, vectors and host cells that contain the BoNT/B binding domain of syt I or II

[00025] The term "isolated polypeptide" or "isolated nucleic acid" used herein means a polypeptide or nucleic acid isolated from its natural environment or prepared using synthetic methods such as those known to one of ordinary skill in the art. Complete purification is not required in either case. The polypeptides and nucleic acids of the invention can be isolated and purified from normally associated material in conventional ways such that in the purified preparation the polypeptide or nucleic acid is the predominant species in the preparation. At the very least, the degree of purification is such that the extraneous material in the preparation does not interfere with use of the polypeptide or nucleic acid of the invention in the manner disclosed herein. The polypeptide or nucleic acid is preferably at least about 85% pure, more preferably at least about 95% pure and most preferably at least about 99% pure.

[00026] Further, an isolated nucleic acid has a structure that is not identical to that of any naturally occurring nucleic acid or to that of any fragment of a naturally occurring genomic nucleic acid spanning more than three separate genes. An isolated nucleic acid also includes, without limitation, (a) a nucleic acid having a sequence of a naturally occurring genomic or extrachromosomal nucleic acid molecule but which is not flanked by the coding sequences that flank the sequence in its natural position; (b) a nucleic acid incorporated into a vector or into a prokaryote or eukaryote genome such that the resulting molecule is not identical to any naturally occurring vector or genomic DNA; (c) a separate molecule such as a cDNA, a genomic fragment, a fragment produced by polymerase chain reaction (PCR), or a restriction fragment; and (d) a recombinant nucleotide sequence that is part of a hybrid gene, i.e., a gene encoding a fusion protein. Specifically excluded from this definition are nucleic acids present in mixtures of clones, e.g., as these occur in a DNA library such as a cDNA or genomic DNA library. An isolated nucleic acid can be modified or unmodified DNA or RNA, whether fully or partially single-stranded or double-stranded or even triple-stranded. A nucleic acid can be chemically or enzymatically modified and can include so-called non-standard bases such as inosine.

[00027] In one aspect, the present invention relates to an isolated polypeptide having an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to that of the BoNT/B binding domain of syt I or II of the rat, mouse or human species. Specifically excluded from the polypeptide of the present invention is one that contains full length syt I or II. In a preferred embodiment, the isolated polypeptide has an amino acid sequence selected

from amino acids 32-52 of SEQ ID NO:2 or 4, amino acids 33-53 of SEQ ID NO:5, amino acids 40-60 of SEQ ID NO:7 or 9, or amino acids 37-57 of SEQ ID NO:10.

[00028] Optionally, the isolated polypeptide of the present invention further contains an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the ganglioside binding domain of syt I or II of the rat, mouse or human species. The BoNT/B binding domain and the ganglioside binding domain on the same polypeptide do not have to be from the same protein and species. For example, a polypeptide of the present invention can contain a BoNT/B binding domain of syt I of one species and a ganglioside binding domain of syt II of another species. The ganglioside binding domains of syt I and II are the same as the transmembrane domains. In a preferred embodiment of the present invention, a polypeptide of the present invention further contains an amino acid sequence selected from amino acids 53-79 of SEQ ID NO:2 or 4, amino acids 54-80 of SEQ ID NO:5, amino acids 61-87 of SEQ ID NO:7 or 9, or amino acids 58-84 of SEQ ID NO:10.

[00029] Examples of the polypeptides of the present invention include but are not limited to those that contain amino acids 32-52 or 32-79 of mouse or rat syt I, amino acids 33-53 or 33-80 of human syt I, amino acids 40-60, 1-61, 1-87, 40-87, 40-267 or 1-267 of mouse or rat syt II, amino acids 37-57, 1-57, 1-84, 37-84, 37-264 or 1-264 of human syt II, or a syt I or II fragment in other animal species that corresponds to any of the foregoing syt I and II fragments. It is understood that substitutions such as conservative substitutions can be introduced into non-critical amino acid positions and this will not materially affect the function of the BoNT/B binding domain of syt I or II. An isolated polypeptide that contains the BoNT/B binding domain of syt I or II with such substitutions is within the scope of the present invention. The isolated polypeptide of the invention can include one or more amino acids at either or both N-terminal and C-terminal ends of the BoNT/B binding domain of syt I or II, where the additional amino acid(s) do not materially affect the function of the domain (binding BoNT/B). Any additional amino acids can, but need not, have advantageous use in purifying, detecting, or stabilizing the polypeptide.

[00030] In order to improve the stability and/or binding properties of a polypeptide, the molecule can be modified by the incorporation of non-natural amino acids and/or non-natural chemical linkages between the amino acids. Such molecules are called peptidomimics (H.U. Saragovi et al. Bio/Technology (1992), Vol 10, 773-778; S. Chen et al., Proc. Natl. Acad. Sci. USA (1992) Vol 89, 5872-5876). The production of such compounds is restricted to chemical synthesis. It is understood that a polypeptide of the present invention can be

modified into peptidomimics without abolishing its function. This can be readily achieved by a skilled artisan.

[00031] In another aspect, the present invention relates to an isolated nucleic acid containing a coding polynucleotide or its complement wherein the coding polynucleotide has an uninterrupted coding sequence that encodes a polypeptide of the invention as set forth above. A nucleic acid containing a polynucleotide that can hybridize to the coding polynucleotide or its complement, under either stringent or moderately stringent hybridization conditions, is useful for detecting the coding polypeptide and thus is within the scope of the present invention. Stringent hybridization conditions are defined as hybridizing at 68°C in 5x SSC/5x Denhardt's solution/1.0% SDS, and washing in 0.2x SSC/0.1% SDS +/- 100 μg/ml denatured salmon sperm DNA at room temperature, and moderately stringent hybridization conditions are defined as washing in the same buffer at 42°C. Additional guidance regarding such conditions is readily available in the art, for example, by Sambrook et al., 1989, Molecular Cloning, A Laboratory Manual, Cold Spring Harbor Press, N.Y.; and Ausubel et al. (eds.), 1995, Current Protocols in Molecular Biology, (John Wiley & Sons, N.Y.) at Unit 2.10. A nucleic acid containing a polynucleotide that is at least 80% identical to the coding polynucleotide or its complement over the entire length of the coding polynucleotide can also be used as a probe for detecting the coding polynucleotide and is thus within the scope of the present invention. Specifically excluded from the present invention is a nucleic acid that contains a nucleotide sequence encoding full length syt I or II.

[00032] In a related aspect, any nucleic acid of the present invention described above can be provided in a vector in a manner known to those skilled in the art. The vector can be a cloning vector or an expression vector. In an expression vector, the polypeptide-encoding polynucleotide is under the transcriptional control of one or more non-native expression control sequences which can include a promoter not natively found adjacent to the polynucleotide such that the encoded polypeptide can be produced when the vector is provided in a compatible host cell or in a cell-free transcription and translation system. Such cell-based and cell-free systems are well known to a skilled artisan. Cells comprising a vector containing a nucleic acid of the invention are themselves within the scope of the present invention. Also within the scope of the present invention is a host cell having the nucleic acid of the present invention integrated into its genome at a non-native site.

Methods for reducing BoNT/B neuro-toxicity

[00033] In another aspect, the present invention relates to a method for reducing BoNT/B cellular toxicity in target cells such as neurons. As a result, botulism disease can be prevented or treated. The term "reducing BoNT/B cellular toxicity" encompasses any level of reduction in BoNT/B toxicity. The BoNT/B toxicity can be reduced by reducing the syt I or syt II protein levels in target cells, by inhibiting BoNT/B-related cellular functions of syt I or II in target cells, or by reducing the binding between BoNT/B and syt I or II located on the cellular surface of target cells. The binding between BoNT/B and syt I or II can be reduced by blocking the binding between BoNT/B and its binding domains on syt I or II, or by reducing the binding between gangliosides and the ganglioside binding domains on syt I or II. A reduction in the above bindings can be readily accomplished by a skilled artisan through either blocking the bindings directly or reducing the amount of syt I, syt II or gangliosides.

Reducing syt I and syt II protein level

[00034] There are many methods by which cellular protein levels such as the levels of syt I and II can be reduced. The present invention is not limited to a particular method employed. As an example, the cellular levels of syt I and II can be reduced using antisense technology. For example, a 20-25mer antisense oligonucleotide can be directed against the 5' end of *syt I* or *II* mRNA with phosphorothioate derivatives on the last three base pairs on the 3' and 5' ends to enhance the half life and stability of the oligonucleotides. A carrier for an antisense oligonucleotide can be used. An example of a suitable carrier is cationic liposomes. For example, an oligonucleotide can be mixed with cationic liposomes prepared by mixing l-alpha dioleylphatidylcelthanolamine with dimethldioctadecylammonium bromide in a ratio of 5:2 in 1 ml of chloroform. The solvent will be evaporated and the lipids resuspended by sonication in 10 ml of saline. Another way to use an antisense oligonucleotide is to engineer it into a vector so that the vector can produce an antisense cRNA that blocks the translation of the mRNAs encoding for syt I and II. Similarly, RNAi techniques, which are now being applied to mammalian systems, are also suited for inhibiting the expression of syt I and II. (See Zamore, Nat. Struct. Biol. 8:746:750 (2001), incorporated herein by reference as if set forth in its entirety).

Dominant negative syt I and II

[00035] In another aspect, the present invention relates to identifying a dominant negative syt I or II that can negate the effects of BoNT/B on cells that express syt I or II. A

dominant negative syt I or II can be identified by introducing a mutation into a *syt I* or *II* gene, expressing the mutated *syt I* or *II* and the wild type *syt I* or *II* in the same host cell and determining the effect of the mutated syt I or II on parameters that relate to BoNT/B toxicity, which include but are not limited to susceptibility of the host cell to BoNT/B, integration of newly formed syt I or II into the host cell membrane, binding of wild type syt I or II to BoNT/B, and uptake of BoNT/B and syt I or II complex into cells. The wild type *syt I* or *II* expressed in the host cell can be the endogenous *syt I* or *II* gene or a *syt I* or *II* gene introduced into the host cell. Any dominant negative syt I or II identified is within the scope of the present invention. The identified dominant negative syt I or II can be used to negate the effect of BoNT/B toxin, which can be readily accomplished by a skilled artisan.

<u>Blocking the binding between BoNT/B and syt I or II</u>

[00036] The identification of syt I and II as BoNT/B receptors as well as the BoNT/B binding sequences on the receptors enables those skilled in the art to block the binding between BoNT/B and its receptors through many familiar strategies. One strategy is to use monoclonal or polyclonal antibodies specific for the BoNT/B binding domains of syt I and II to block the BoNT/B binding sites on syt I and II. Since gangliosides are required for BoNT/B to bind syt I and they also enhance the binding between BoNT/B and syt II, antibodies specific for the ganglioside binding domains on syt I and II can also be used to block or reduce the binding between BoNT/B and syt I or II. Given that the amino acid sequences of the BoNT/B and ganglioside binding domains of syt I and II are disclosed here, it is well within the capability of a skilled artisan to generate monoclonal or polyclonal antibodies specific for these domains. The antibodies so generated are within the scope of the present invention.

[00037] Another strategy to block the binding between BoNT/B and syt I or II is to use a polypeptide having an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to a BoNT/B binding domain of syt I or II of the rat, mouse or human species, including syt I and II themselves, to compete with syt I or II located on the cellular surface of target cells for BoNT/B binding. Preferred polypeptides of the present invention contains a BoNT/B binding domain of syt I or II of the rat, mouse or human species. To block the binding between BoNT/B and syt I or II in a specific species, a syt I or II BoNT/B binding domain of the same species or a different species can be used. Since syt I needs gangliosides to bind BoNT/B, the polypeptide that contains a syt I BoNT/B binding domain-related sequence should also contain an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to a

ganglioside binding domain of the rat, mouse or human species, and gangliosides should also be employed. In a preferred embodiment of the method, a ganglioside binding domain of the rat, mouse or human species is used. The ganglioside binding domain on a polypeptide of the present invention can be from either syt I or syt II and of the same or different species as the BoNT/B binding domain of syt I. Preferably, the ganglioside binding domain is that of syt I and of the same species as the BoNT/B binding domain. The employment of gangliosides is optional when the polypeptide is used for competing with syt II on target cells. Suitable polypeptides that can be used in the present invention include but are not limited to those that contain amino acids 32-79 of mouse or rat syt I, amino acids 33-80 of human syt I, amino acids 40-60, 1-61, 1-87, 40-87, 40-267, 1-267 and 1-422 of mouse or rat syt II, amino acids 37-57, 1-58, 1-84, 37-84, 37-264, 1-264 and 1-419 of human syt II, and fragments in other animal species that correspond to the foregoing syt I and II fragments. The polypeptide can be introduced into a human or nonhuman subject by administering the polypeptide directly or a vector that can express the polypeptide in the human or nonhuman subject.

[00038] Those skilled in the art understand that mutations such as substitutions, insertions and deletions can be introduced into the BoNT/B binding domains of syt I and II without abolishing their BoNT/B binding activity. Some mutations may even enhance the binding activity. A polypeptide containing such mutants can obviously be used in the method of the present invention. The syt I and II BoNT/B binding domain mutants that retain the BoNT/B binding activity can be identified by using the screening methods described below.

<u>Identifying agents that can block binding between BoNT/B and syt I or II</u>

[00039] Agents that can block binding between BoNT/B and syt I or II can be screened by employing BoNT/B and a polypeptide that contains either a BoNT/B binding domain of syt I and a ganglioside binding domain of syt I or II, or a BoNT/B binding domain of syt II, under conditions suitable for BoNT/B to bind the polypeptide. Gangliosides are included when the method is used for screening for agents that can block BoNT/B-syt I binding. For BoNT/B-syt II screening, the inclusion of gangliosides and the ganglioside binding domain of syt II on the polypeptide is optional. The binding between BoNT/B and the polypeptide can be measured in the presence of a test agent and compared to that of a control that is not exposed to the test agent. A lower than control binding in the test agent group indicates that the agent can block binding between BoNT/B and syt I or II. The BoNT/B binding domain or ganglioside binding domain of syt I or II used here are that of the rat, mouse or human species. A polypeptide that contains an amino acid sequence that is at least 70%, 80%, 90%

or 95% identical to the BoNT/B binding domain or ganglioside binding domain of syt I or II can also be used in the method. The preferred polypeptides for the screening assay are the BoNT/B and ganglioside binding domains of syt I and the BoNT/B binding domain of syt II.

[00040] There are many systems that a skilled artisan is familiar with for assaying the binding between BoNT/B and the BoNT/B binding domain on syt I or II. Any of these systems can be used in the screening method. Detailed experimental conditions can be readily determined by a skilled artisan. For example, the binding between BoNT/B and the polypeptide described above can be measured *in vitro* (cell free system). A cell culture system in which syt I or II are expressed and translocated onto the cellular membrane can also be used. For the cell culture system, in addition to the binding between BoNT/B and syt I or II, the entry of BoNT/B into the cells and a number of other parameters such as those disclosed in the examples below, can also be used as an indicator of binding between BoNT/B and syt I or II.

[00041] Any method known to one of ordinary skill in the art for measuring protein-protein interaction can be used to measure the binding between BoNT/B and the BoNT/B binding domain of syt I or II. For example, coimmunoprecipitation and affinity columns are two methods commonly used. Another method that can be used is surface plasmon resonance (SPR). SPR uses changes in refractive index to quantify binding and dissociation of macromolecules to ligands covalently linked onto a thin gold chip within a micro flow cell. This technique has been used to study protein-protein interactions in many systems, including the interactions of PA63 with EF and LF (Elliott, J.L. et al., Biochemistry 39:6706-6713, 2000). It provides high sensitivity and accuracy, the ability to observe binding and release in real time, and consumption of only minute quantities of protein. Besides the equilibrium dissociation constant (Kd), on- and off-rate constants (ka and kd) may also be obtained. Typically, a protein to be studied is covalently tethered to a carboxymethyl dextran matrix bonded to the gold chip. Binding of a proteinaceous ligand to the immobilized protein results in a change in refractive index of the dextran/protein layer, and this is quantified by SPR. A BIAcore 2000 instrument (Pharmacia Biotech) can be used for these measurements.

[00042] For the cell culture system, the binding of BoNT/B to syt I or II can be assayed by staining the cells, the examples of which are described in the examples below.

Identifying agents that bind BoNT/B binding domain of syt I or II

[00043] Agents that can bind to the BoNT/B binding domain of syt I or II can be used to block the binding between BoNT/B and syt I or II. Such agents can be identified by

providing a polypeptide that contains a BoNT/B binding domain of syt I or II to a test agent, and determining whether the agent binds to the BoNT/B binding domain. The BoNT/B binding domain or ganglioside binding domain of syt I or II used here are that of the rat, mouse or human species. A polypeptide that contains an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the BoNT/B binding domain of syt I or II can also be used in the method. The preferred polypeptides are the BoNT/B binding domains of syt I and syt II themselves. Optionally, agents identified by the method is further tested for the ability to block BoNT/B entry into cells or to neutralize BoNT/B toxicity. A skilled artisan is familiar with the suitable systems that can be used for the further testing. Examples of such systems are provided in the examples below.

[00044] The skilled artisan is familiar with many systems in the art for assaying the binding between a polypeptide and an agent. Any of these systems can be used in the method of the present invention. Detailed experimental conditions can be readily determined by a skilled artisan. For example, a polypeptide that contains amino acids the BoNT/B binding domain of syt I or II can be provided on a suitable substrate and exposed to a test agent. The binding of the agent to the polypeptide can be detected either by the loss of ability of the polypeptide to bind to an antibody or by the labeling of the polypeptide if the agent is labeled with radioactivity, fluorescence or other features. In another example, a polypeptide that contains the BoNT/B binding domain of syt I or II can be expressed in a host cell, and the cell is then exposed to a test agent. Next, the polypeptide can be isolated, e.g., by immunoprecipitation or electrophoresis, and the binding between the polypeptide and the agent can be determined. As mentioned above, one way to determine the binding between the polypeptide and the agent is to label the agent with radioactivity or fluorescence so that the polypeptide that binds to the agent becomes radioactive or fluorescent upon binding. If the test agent is a polypeptide, examples of specific techniques for assaying protein/protein binding as described above can also be used. It should be noted that when the BoNT/B binding domain of syt I or II used in the screening assay have flanking sequences, it may be necessary to confirm that an agent binds to the BoNT/B binding domain rather than the flanking sequences, which can be readily accomplished by a skilled artisan.

Agents that can be screened

[00045] The agents screened in the above screening methods can be, for example, a high molecular weight molecule such as a polypeptide (including, e.g., a polypeptide containing a mutant BoNT/B binding domain of syt I or II, or a monoclonal or polyclonal

antibody to the BoNT/B binding domain or the full length of syt I or II), a polysaccharide, a lipid, a nucleic acid, a low molecular weight organic or inorganic molecule, or the like.

[00046] Batteries of agents for screening are commercially available in the form of various chemical libraries including peptide libraries. Examples of such libraries include those from ASINEX (i.e. the Combined Wisdom Library of 24,000 manually synthesized organic molecules) and CHEMBRIDGE CORPORATION (i.e. the DIVERSet™ library of 50,000 manually synthesized chemical compounds; the SCREEN-Set™ library of 24,000 manually synthesized chemical compounds; the CNS-Set™ library of 11,000 compounds; the Cherry-Pick™ library of up to 300,000 compounds) and linear library, multimeric library and cyclic library (Tecnogen (Italy)). Once an agent with desired activity is identified, a library of derivatives of that agent can be screened for better molecules. Phage display is also a suitable approach for finding novel inhibitors of the interaction between BoNT/B and syt I or II.

Methods of detecting BoNT/B or *Clostridium botulinum*

[00047] In another aspect, the present invention relates to a method of detecting BoNT/B or *Clostridium botulinum*. The method involves exposing a sample suspected of containing BoNT/B to an agent that contains a polypeptide having a BoNT/B binding domain of syt I and a ganglioside binding domain of syt I or II, or a BoNT/B binding domain of syt II, and detecting binding of the polypeptide to BoNT/B. When the BoNT/B and ganglioside binding domains of syt I are used, gangliosides are also provided in the agent. When the BoNT/B binding domain of syt II is used, the inclusion of gangliosides and the ganglioside binding domain of syt II on the polypeptide is optional. The BoNT/B binding domain or ganglioside binding domain of syt I or II used here are that of the rat, mouse or human species. A polypeptide with an amino acid sequence that is at least 70%, 80%, 90% or 95% identical to the BoNT/B binding domain or ganglioside binding domain of syt I or II can also be used in the method.

Kits

[00048] Any product of the invention described herein can be combined with one or more other reagent, buffer or the like in the form of a kit useful, e.g., for diagnostic, preventive or therapeutic purposes, in accord with the understanding of a skilled artisan.

[00049] The invention will be more fully understood upon consideration of the following non-limiting examples.

Example

Materials and Methods

[00050] *Cell lines, gangliosides and toxins* - A syt I deficit (Syt I⁻) PC12 cell line was kindly provided by Y. Shoji-Kasai and M. Takahashi (Tokyo, Japan) (Shoji-Kasai et al., 1992). A mixture of bovine brain gangliosides (18% GM_1, 55% GD_{1a}, 10% GT_{1b}, and 2% other gangliosides), hereafter designated as gangliosides, were obtained from Calbiochem. BoNT/A, B and E were purified as described (Dasgupta et al., 1970; Evans et al., 1986; Schmidt and Siegel, 1986).

[00051] *Antibodies* - Monoclonal antibodies directed against syb II (69.1), syt I (α-syt I_N; 604.4, α -syt I_C; 41.1), α/β-SNAP (77.1) and SNAP-25 (71.2) were provided by R. Jahn and S. Engers (Gottingen, Germany). Rabbit polyclonal antibodies directed against syt II were kindly provided by M. Fukuda (Ibaraki, Japan) (Fukuda and Mikoshiba, 2000). Anti-BoNT/A, B and E antibodies were generated by immunizing rabbits with formalin treated purified neurotoxin; antibodies were affinity purified using immobilized neurotoxin.

[00052] *cDNA and recombinant proteins* - cDNA encoding rat syt I (Perin et al., 1990), mouse syt II and IX (Fukuda and Mikoshiba, 2000), and rat syt IV (Vician et al., 1995) were provided by T.C. Sudhof (Dallas, TX), M. Fukuda (Ibaraki, Japan) and H. Herschman (Los Angeles, CA), respectively. Full length syb II was generated as a GST-fusion protein as described (Lewis et al., 2001) using a cDNA provide by R. Scheller (Stanford, CA).

[00053] To screen for toxin binding activity, we generated truncated versions of syt I, II, IV and IX that lacked the C2B-domain but contained all other domains. A number of additional constructs (truncations and chimeras, as indicated in the figures) were also generated by PCR, subcloned into pGEX-2T and expressed and purified as described (Chapman et al., 1996; Lewis et al., 2001). Syt II 1-267 and 61-267 were also subcloned into pTrcHis and purified as N-terminal tagged His6 fusion proteins as described (Chapman et al., 1996).

[00054] *Pull-down assays* - Recombinant proteins were immobilized as GST fusion proteins bound to glutathione-Sepharose beads. Unless otherwise indicated, 10 μg of immobilized protein was mixed with the indicated concentrations of BoNT/B, A or E either with (+; 25 μg/ml) or without (-) gangliosides in 100 μl of Tris buffered saline (TBS; 20 mM Tris, 150 mM NaCl, pH 7.4) plus 0.5% Triton X-100 for 1 hour at 4°C. Beads were washed three times, bound proteins were solubilized by boiling in SDS-sample buffer and subjected

to SDS-PAGE and visualized by staining with Coomassie Blue or by immunoblot analysis using anti-toxin antibodies. In all blots, the immunoreactivity for the toxin heavy chain is shown.

[00055] A peptide corresponding to residues 40-60 of mouse syt II, P21, and a scrambled version of this peptide, P21S (IKMNDAEFFGKSNFQEKLEKEC, SEQ ID NO:5), were synthesized (Biotech Center, UW-Madison) with an added C-terminal cys which was used to conjugate them to agarose beads (at 1 mg/ml) using a Sulfolink Kit (Pierce). Fifty μl of the conjugated agarose gel was used in the pull down assays.

[00056] *PC12 cell lines and immunoblot analysis* – PC12 cells were cultured as described (Klenchin et al., 1998). To generate cells that express syt II (syt II^+), full length mouse syt II was subcloned into pCDNA3.1(-) (ClonTech) and transfected into PC12 cells via electroporation. Transfected cells were selected with G418 (1 mg/ml) and several independent monoclonal cell lines were established. Cells were harvested in PBS plus 0.5% Triton X-100, 0.05% SDS and 5 mM PMSF, and incubated for 30 min at 4°C on a shaker. Samples were centrifuged at 21,000 x g for 10 min, and the concentration of protein in the supernatant was determined using BCA (Pierce). Samples were subjected to SDS-PAGE and immunoblot analysis; blots were developed using enhanced chemiluminescence (ECL) (Pierce).

[00057] *Entry of BoNTs into PC12 cells* - In experiments that did not involve pre-loading, cells were grown to 70% confluence and incubated with BoNT for 48 hrs. For experiment in which cells were pre-loaded with gangliosides, cells were grown to 80% confluence followed by incubation in serum-free media plus 250 μg/ml gangliosides. Twenty four hrs later, the serum-free/ganglioside media was replaced with complete media and the cells were incubated with toxin for 48 hrs. Cells were harvested and entry of CNTs was assayed via immunoblot analysis using antibodies directed against syb II or SNAP-25.

[00058] For blocking experiments, syt II 1-267 and syt II 61-267 were generated as his6-fusion proteins; syt II 1-87 was generated as a GST-fusion protein that was eluted from beads using 10 mM glutathione plus 0.5% Triton X-100. Protein fragments or peptides were pre-mixed with BoNT/B in 200 μl TBS for 1 hr at 4°C before adding into 2 ml of cell culture media (per well in a 6 well plate). In some cases, gangliosides were also added in the binding buffer (Fig. 5 B, lower panel). The final concentration of BoNT/B was 30 nM, the final concentration of gangliosides was 25 μg/ml, and the final [syt fragment] is indicated in the description of the drawings

[00059] *Binding of BoNT/B to PC12 cells* - Cells treated with toxin, plus or minus pre-incubation with syt fragments, were washed three times with PBS, fixed with 4% paraformaldehyde (15 min at room temperature), permeabilized with 0.1% Triton X-100 (10 min at room temperature), and stained with a rabbit anti-BoNT/B primary antibody and an FITC conjugated goat anti-rabbit secondary antibody (Jackson Laboratories). In the syt II fragment competition assays described in Fig. 5, syt II 1-267 and 61-267 fragments form aggregates bound to cells (Bai et al., 2000) - these were visualized using a mouse anti-his6 primary antibody (Qiagen) and a Rhodamine-conjugated goat anti-mouse secondary antibody (Jackson Laboratories). The fluorescence images were obtained as described for the motor nerve terminal experiments. We note that for these experiments free detergent was removed from the recombinant syt fragments by washing the immobilized proteins with detergent-free buffers prior to elution. However, in the case of syt II 1-87, low levels of Triton X-100 were needed to elute the protein from the beads; because of this, experiments using this fragment were carried out within 6 hrs to avoid effects of detergent on the cells.

[00060] *Antibody and toxin uptake experiments* – Cells were treated with either control solution (15 mM HEPES, 145 mM NaCl, 5.6 mM KCl, 2.2 mM $CaCl_2$, 0.5 mM $MgCl_2$, 5.6 mM glucose, 0.5 mM ascorbic acid, 0.1% BSA, [pH 7.4]), or high [K^+] solution (same as control solution but adjusted to 95 mM NaCl and 56 mM KCl), for 10 min at 37°C, in the presence of BoNT/B plus 10 μl monoclonal antibody against the luminal (α-syt I_N; clone 604.4) or cytoplasmic domain of syt I (α-syt 1_c; clone 41.1). Cells were washed with culture media, incubated for 30 min 37°C, fixed and permeabilized. A rabbit anti-BoNT/B primary antibody was used to stain BoNT/B; staining was visualized using an FITC conjugated goat anti-rabbit secondary antibody. Rhodamine conjugated goat anti-mouse secondary antibodies were used to visualize internalized syt I antibodies. Confocal images were collected with a Bio-Rad MRC 1000 confocal microscope (Keck Center for Biological Imaging, UW-Madison) using a 100X oil-immersion objective.

[00061] *Co-immunoprecipitation* – Recombinant syt I 1-265 GST was purified as described above and cleaved from the GST tag using thrombin. Five μl of monoclonal antibody α-syt I_N (604.4) was incubated with BoNT/B (300 nM), with or without 1.5 μM Syt I 1-265, in 100 μl TBS plus 0.5% Triton X-100 and gangliosides (25 μg/ml), for 1 hr at 4 °C. Thirty μl Protein G fast flow beads (Pharmacia) was added, samples were mixed for 1 hr, beads were washed three times in binding buffer, and bound material was analyzed by SDS-PAGE and immunoblotting using an anti-BoNT/B polyclonal antibody and α-syt I_N (604.4).

[00062] *Rat hemi-diaphragm experiments* - Rats hemi-diaphragms were placed in ice-cold ringer (in mM: NaCl 138.8, KCl 4, $NaHCO_3$ 12, KH_2PO_4 1, $MgCl_2$ 2, $CaCl_2$ 2, glucose 11) gassed with 95% CO_2/5% O_2. Stimulation was carried out with a similar solution where KCl was increased to 45 mM, and the NaCl appropriately reduced. Hemi-diaphragms were incubated with high potassium ringer containing 5 nM BoNT/B for 10 min at room temperature. In some experiments the BoNT/B was pre-mixed with either the syt II fragment 1-267, or fragment 61-267, both mixed with 25 μg/ml gangliosides. At the end of the stimulation/incubation period, the preparations were fixed (4% paraformaldehyde), permeabilized (0.3% Triton X-100), and blocked in goat serum prior to immunolabeling with a rabbit anti-BoNT/B antibody and a monoclonal anti-Syb II antibody. Immunofluorescence was visualized using a FITC-conjugated anti-rabbit antibody, and a TRITC-conjugated anti-mouse antibody. A region of muscle adjacent to the site of nerve entry (where a large number of surface nerve terminals are to be found) was placed in a viewing chamber with a glass bottom comprising a single cover slip. Immunofluorescence images were obtained using a Nikon TE300 microscope, with a microMAX cooled CCD camera controlled by MetaMorph software. Fluorescence intensities were quantified using ImageJ software.

[00063] *Neutralization of BoNT/B activity in vivo* - For each batch of BoNT/B, the LD_{50} value for mice (20-22 g; Institute of Cancer Research strain) was determined using standard methods (Schantz and Kautter, 1978). The LD_{50} corresponds to the amount of toxin, introduced via intra peritoneal injection, that results in 50% death after 4 days. Our preparations of BoNT/B had activities of about 10^8 LD_{50}/mg. For toxin neutralization studies, we made use of the more rapid intravenous time-to-death assay (Boroff and Fleck, 1966). We first generated a standard curve in which the relationship between time-to-death of mice injected, intravenously, with 100 μl BoNT/B (expressed in min) is plotted versus the specific toxicity of BoNT/B that was determined using the standard method described above (log [LD_{50}/ml]). Within the linear range, 10^4-10^6 LD_{50}/ml, this plot was used to convert experimentally determined time-to-death, from intravenous injection of relatively large doses of toxin, to LD_{50}/ml values. For the toxin neutralization experiments, BoNT/B was premixed with gangliosides alone (250 μg/ml) or gangliosides plus the indicated syt II fragments for 10 min at room temperature and then injected intravenously into mice. In all experiments, the total injection volume was always 100 μl. Neutralization of the toxin is indicated by an extension in the time-to-death of mice injected with toxin alone versus injection with toxin that had been pre-mixed wit syt fragments/gangliosides. The increase in the time-to-death was converted into a decrease in the apparent [LD_{50}/ml] using the standard curve, and the

percentage of neutralization was calculated using the expression: 1- [LD_{50}/ml(+ syt II fragment)/ LD_{50}/ml (- syt II fragment)] x 100, where (+ syt II fragment) refers to samples that contain toxin, gangliosides and recombinant proteins and (-syt II fragment) samples were composed of toxin and gangliosides only.

Results

[00064] *A region within the luminal domain of syt I and II mediates direct interactions with BoNT/B* - To assay for direct syt•BoNT interactions, fragments of syt I and II were immobilized as GST fusion proteins and used as an affinity matrix to pull down BoNT/A, B or E in the presence and absence of gangliosides. For these experiments, we included two other syt isoforms, syt IV and IX, as well as full length syb II, as negative controls. The structure of the syt fragments are shown in Fig. 1A (upper panel). Because each fragment contains a transmembrane domain, binding assays included 0.5% Triton X-100; thus, gangliosides were presented as mixed micelles. In contrast to a previous study (Li and Singh, 1998), we did not observe detectable binding of BoNT/A or E to any of the immobilized proteins (Fig. 1A, middle panel), even when relatively high concentrations of BoNT/A and E were employed (300 nM; data not shown), indicating that these toxins do not bind to the syt fragments used in our assays.

[00065] Under identical conditions, we observed that BoNT/B binds syt I and II. While syt I•BoNT/B interactions were strictly dependent on gangliosides, syt II bound BoNT/B in the absence of gangliosides (Fig. 1A, middle panel). Reducing the concentration of bead-immobilized GST-syt II fusion protein revealed that gangliosides can enhance syt II•BoNT/B interactions (Fig. 1A, lower panel), but this interaction is clearly less dependent on gangliosides. These findings are consistent with previous data showing that syt II binds BoNT/B more tightly than does syt I (Nishiki et al., 1996a); presumably, the higher affinity syt II•BoNT/B interaction is less reliant on gangliosides. Syt I/II•BoNT/B interactions are specific, since binding to an analogous region of syt IV or IX, or to full length syb II, was not detected (Fig. 1A, middle panel).

[00066] If syt I and II are physiologically relevant receptors for BoNT/B, binding must be mediated by the region of syt that is exposed outside of cells - i.e. the luminal domain - during cycles of exocytosis and endocytosis. To clarify how BoNT/B binds to syt II, we first used syt II/IX chimeras. Swapping the luminal domains of these proteins was sufficient to transfer the BoNT/B binding activity from syt II to syt IX (Fig. 1B), indicating that BoNT/B binding is mediated by the luminal domain of syt II. Consistent with this finding, a shorter

fragment of syt II, composed of only the luminal and transmembrane domain (residues 1-87), mediated stoichiometric binding of the toxin (Fig. 1C).

[00067] Truncation analysis was used to further map the toxin binding site of syts I and II. Within the luminal domain of syt II, residues 40-60, which are adjacent to the transmembrane domain, are critical for toxin binding (Fig. 2A). We note that fragment 61-267 of syt II can bind gangliosides via its transmembrane domain (residues 61-87) (Kozaki et al., 1998), yet this fragment fails to bind BoNT/B in the presence of gangliosides (Fig. 2A, middle panel). These data suggest that gangliosides do not directly mediate toxin binding under our assay conditions, but rather cooperate with the luminal domain to form high affinity BoNT/B binding sites. The analogous membrane proximal region of syt I (residues 32-52) was also critical for binding of BoNT/B (Fig. 8). This segment is highly conserved between syt I and II (Fig. 2B); minor sequence differences may account for the differences in affinity for BoNT/B (Nishiki et al., 1996a). We note that the isolated luminal domain of syt II (residues 1-61) but not syt I (residues 1-53), bound to BoNT/B (Fig. 2A and Fig. 8). This result is likely due to the strong ganglioside requirements for syt I•BoNT/B interactions; deletion of the transmembrane domain of syt I abolishes ganglioside binding (Kozaki et al., 1998) and thereby decreases BoNT/B binding activity.

[00068] The mapping studies described above suggest that residues 40-60 of syt II comprise the BoNT/B binding domain. To test this directly, a synthetic peptide (P21) corresponding to this segment of syt II was immobilized on beads and used as an affinity matrix. This peptide binds directly to BoNT/B, although less avidly than do longer fragments of syt II since detectable binding required higher concentrations of the toxin (Fig. 2C, upper panel). A scrambled version of this peptide, P21S, served as the negative control. Furthermore, P21, but not P21S, was able to competitively inhibit syt II•BoNT/B interactions (Fig. 2C, lower panel). P21 also inhibited syt I•BoNT/B interactions (data not shown). Together, these studies establish that residues 40-60 of syt II largely mediate binding of BoNT/B.

[00069] *Syt I mediates ganglioside dependent binding and entry of BoNT/B into PC12 cells* - The experiments described above demonstrate that syt I and II bind to BoNT/B through a conserved region in their ecto-domains. The key question, however, is whether syt I or II mediate entry of the toxin; namely, are they functional protein receptors for BoNT/B? To address this question we first used PC12 cells, a neuroendocrine cell line that serves as a model system to study Ca^{2+} triggered exocytosis. These cells express the substrates for all of the CNTs but are resistant to entry of BoNT/B, probably due to lack of functional toxin

receptors (Lomneth et al., 1991). PC12 cells express syts I and IX and trace levels of syt IV; other syt isoforms are not expressed at significant levels (Zhang et al., 2002). Since syt IX and IV do not bind BoNT/B and syt I binds only in the presence of gangliosides (Fig. 1A, middle panel), toxin resistance could be due to the fact that these cells contain low levels of gangliosides as compared to neurons (Walton et al., 1988). We tested this idea by pre-loading exogenous gangliosides into the plasma membrane of wild type PC12 cells. As shown in Fig. 3A, detectable toxin binding was observed only when cells were loaded with gangliosides. We then determined whether the toxin can enter ganglioside-treated cells. To monitor entry we assayed for cleavage of the cytoplasmic substrate of BoNT/B, syb II (Schiavo et al., 1992) by immunoblot analysis using anti-syb II antibodies. Cleavage of syb II by BoNT/B occurred only when cells were first pre-loaded with gangliosides (Fig. 3B). These data are consistent with a model in which syt I and gangliosides cooperate to mediate the binding and entry of BoNT/B, and are in agreement with biochemical data showing that the toxin binds to syt I only in the presence of gangliosides. To further test this model, we took advantage of a PC12 cell line that lacks syt I (Syt I^-) (Shoji-Kasai et al., 1992). This cell line is still capable of Ca^{2+}-triggered exocytosis, presumably via the redundant action of syt IX (Fukuda et al., 2001; Zhang et al., 2002). As shown in Fig. 3C, BoNT/B failed to cleave syb II in ganglioside-loaded syt I- PC12 cells. These data indicate that gangliosides plus syt I are both needed for toxin entry.

[00070] We also assayed for entry of BoNT/A and E into PC12 cells. Entry was monitored by assaying for cleavage of their substrate SNAP-25 (Blasi et al., 1993a; Schiavo et al., 1993). BoNT/A cleaves SNAP-25 between residues 197-198, thereby removing 9 amino acids; BoNT/E cleaves between residues 180-181 and removes 26 residues (Schiavo et al., 1993). Incubation of cells with nM concentrations of BoNT/A and E resulted in similar degrees of cleavage of SNAP-25 in both wild type (data not shown) and syt I- cells (Fig. 3D). Thus, both toxins are able to enter syt I- PC12 cells that have not been pre-loaded with gangliosides. These experiments demonstrate that syt I/II are not required for entry of BoNT/A and E into PC12 cells, and that syt I- cells are competent to take-up at least some CNTs.

[00071] *Syt II is sufficient to mediate entry of BoNT/B into PC12 cells* - To determine directly whether syt II can function as a receptor for BoNT/B, we took advantage of the observation that this syt isoform is able to bind BoNT/B to some extent in the absence of gangliosides (Fig. 1A). We generated PC12 cell lines that stably express syt II (Syt II^+; Fig. 4A) and observed that they bind BoNT/B without preloading cells with exogenous

gangliosides (Fig. 4B). A key finding was that expression of syt II was sufficient to reconstitute toxin entry into the transfected cells, as shown by the cleavage of syb II (Fig. 4C). The efficiency of cleavage was proportional to the level of syt II expression, and cleavage was not observed in cells lacking syt II (Fig. 4C, right panel). These findings demonstrate that syt II can function as a receptor for BoNT/B without pre-loading cells with exogenous gangliosides.

[00072] To further test whether binding and entry is mediated by direct interactions between BoNT/B and the luminal domain of syt II, we determined whether fragments of syt II that contain the BoNT/B binding site inhibit toxin action. As shown in Fig. 5A, fragments corresponding to residues 1-267, 1-87 and 40-60 (P21) of syt II, blocked binding of BoNT/B to syt II+ PC12 cells. Syt II fragment 61-267, which lacks the luminal domain, and the scrambled peptide P21S, failed to block binding of the toxin. We note that syt II 1-267 and 61-267 contain an oligomerization domain within residues 61-140, and also bind membranes via their C2A-domain, thus forming aggregates (Bai et al., 2000). These aggregates are visualized in Fig. 5A (bottom panels) using an anti-his6 antibody that recognizes a his6-tag present in these recombinant syt fragments. The syt 1-267 fragment also contains bound BoNT/B, as shown via the anti-BoNT/B immunoreactivity in the syt II aggregates (Fig. 5A, upper panel). In contrast, cell-associated syt II 61-267 aggregates did not contain BoNT/B (Fig. 5A, lower panel).

[00073] More importantly, titration of syt II 1-267 resulted in the dose-dependent protection of syb II cleavage; fragment 61-267 had no protective effect (Fig. 5B, upper panel). Inclusion of gangliosides increased the efficacy of protection by about 3-fold (Fig. 5B, lower panel), presumably by facilitating the already robust binding of syt II 1-267 to BoNT/B (Fig. 1A, lower panel). This result is consistent with the observation that the binding partner with the highest affinity for BoNT/B is composed of syt II plus gangliosides (Fig. 1A, lower panel; (Nishiki et al., 1996a)). As a control, mixtures of gangliosides and syt II fragment 61-267 were not able to prevent cleavage of syb II (Fig. 5B, lower panel). P21 also yielded dose-dependent protection, albeit at >10-fold higher concentrations as compared to the 1-267 fragment (Fig. 5C), presumably because it binds less tightly to BoNT/B than the longer fragments of syt II. There is a concern that low levels of detergent associated with the transmembrane domains present in some of the syt fragments may affect the uptake and action of the toxin. However, we did not observe any apparent toxicity using these fragments. Also, the ability of fragment 1-267 to block the action of the toxin cannot be due

to toxicity from associated detergent, as fragment 61-267 has the same transmembrane domain yet fails to provide any protection.

[00074] *Activity dependent entry of BoNT/B into vesicles that contain syt I* - The data above suggest a model in which BoNT/B gains entry into PC12 cells by binding to the luminal domain of syt I or II. This model predicts that BoNT/B will follow the internalization of syt I/II from the cell surface into the same organelles and that internalization should be activity-dependent. The exocytosis/endocytosis of vesicles can be tracked using antibodies directed against the N-terminal luminal domain of syt I (Juzans et al., 1996; Mateeoli et al., 1992). First, we demonstrated that an anti-syt I luminal domain antibody (α-syt I_N) and BoNT/B can bind to syt I simultaneously (Fig. 9A). This is the expected result, since the antibody recognizes the first twelve amino acids at the N-terminus of syt I, while the BoNT/B binding site lies at the C-terminal end of the luminal domain.

[00075] We took advantage of this finding and determined whether the antibody and toxin are taken-up into the same compartment in response to stimulation. PC12 cells were pre-loaded with gangliosides and depolarized with high [K+] to induce exocytosis of secretory vesicles in the presence of α-syt I_N antibodies and BoNT/B. Exocytosis and endocytosis were allowed to proceed for 10 minutes, followed by extensive washes to remove surface-bound antibody and toxin. Both α-syt I_N antibodies and BoNT/B were observed to be internalized into the same compartment. Depolarization of cells significantly increased the internalization of both the antibody and BoNT/B; only low levels of internalization, due to spontaneous exocytosis and recycling, were observed in the control.

[00076] In contrast to the α-syt I_N antibody, an antibody directed against the cytoplasmic domain of syt I (α-syt I_C) was not taken-up (Fig. 9B), demonstrating that staining with the luminal domain antibody is not due to loss of integrity of the cell membranes. Also, α-syt I_N antibodies and BoNT/B were not taken-up into syt I^- PC12 cells (Fig. 9B), further establishing that uptake requires the exposure of the syt I luminal domain and is not due to bulk endocytosis. These findings demonstrate that the luminal domain of syt I is exposed on the surface of PC12 cells during exocytosis, and that BoNT/B enters PC12 cells via organelles that contain syt I. This latter observation was further confirmed by the co-localization of BoNT/B with an antibody directed against the cytoplasmic domain (α-syt I_C) of syt I.

[00077] Similar results were obtained using syt II^+ PC12 cells - BoNT/B entered syt I containing vesicles in an activity dependent manner (data not shown). We have been unable to localize syt II in the syt II^+ cell lines using currently available antibodies. However, syt II

is co-localized with syt I on secretory vesicles in brain and is likely to be targeted to syt I containing organelles in PC12 cells (Osborne et al., 1999).

[00078] *Activity dependent uptake of BoNT/B into motor nerve terminals* - The cause of death from BoNT/B intoxication is asphyxiation due to blockade of neurotransmission at the diaphragm. We therefore extended our studies to explore the mechanism of toxin entry into neurons in this tissue. Only low levels of association of BoNT/B with motor nerve terminals in the rat diaphragm were observed under resting conditions. However, stimulation with KCl results in a dramatic increase in the levels of BoNT/B (5.7-fold; Fig. 6A), and a concomitant loss of syb II immunoreactivity (3.2-fold; Fig. 6B). The increase in binding of BoNT/B and the loss of syb II were virtually abolished by incubation with the syt II fragment 1-267/gangliosides, but not by a mixture of syt II 61-267/gangliosides (Fig. 6A,B). These data demonstrate that uptake of BoNT/B is activity dependent at its natural target. Moreover, binding and entry of the toxin can be prevented by syt II fragments that contain the toxin binding site while syt fragments lacking the toxin binding site have no effect.

[00079] *Competitive inhibition of syt•BoNT/B interactions neutralizes BoNT/B in vivo* - The experiments described above demonstrate that BoNT/B enters PC12 cells and motor nerve terminals through interactions with syt I/II plus gangliosides. To further establish the physiological relevance of the above findings, we determined whether syt II fragments that contain the BoNT/B binding site can neutralize the effects of the toxin *in vivo*. For these studies, we used a rapid method to evaluate toxicity in which the intravenous injection of large amounts (10^5-10^6 LD_{50}) of BoNT/B into mice result in death on a time scale of minutes to hours, as opposed to standard four day lethality assays (in which 1 LD_{50} is defined as the amount of toxin that results in 50% death after four days) (Boroff and Fleck, 1966; Schantz and Kautter, 1978). This assay reduces the amount of time that animals are exposed to the toxin. To this end, we first established a standard curve to relate classically determined LD_{50}/ml values to the time-to-death values that were determined using the rapid assay (Fig. 7A). This plot was then used to convert the experimentally measured time-to-death to units of apparent LD_{50}/ml. After this conversion, the apparent LD_{50}/ml values were used to calculate the % neutralization of the toxin by syt/ganglioside mixtures.

[00080] The range of [syt II 1-267] that we tested in mice did not afford substantial protection in the absence of gangliosides. Syt II fragments 1-267 and 1-87, together with gangliosides, neutralized most of the BoNT/B toxicity in mice (Fig. 7B). We believe that in order for syt II 1-267 itself to provide protection *in vivo*, higher doses are required.

[00081] Syt II 61-267 plus gangliosides did not neutralize the toxin (Fig. 7B), further establishing the essential role of the luminal domain of syt II for toxin entry *in vivo*. The potencies of syt II 1-267 and 1-87 were determined (Fig. 7C); both fragments yielded dose-dependent protection at sub-μM concentrations. Finally, prior intravenous injection with syt II 1-267 or 1-87, mixed with gangliosides, neutralized 70-80% of BoNT/B that was injected 1 minute later (Fig. 7D), indicating that animals can be protected prior to exposure to toxin.

[00082] The present invention is not intended to be limited to the foregoing examples, but rather to encompass all such variations and modifications as come within the scope of the appended claims.

References

(All of which are herein incorporated by reference in their entirety)

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